APPLICATION FOR UNITED STATES LETTERS PATENT

for

WATER CONTENT PROBE

Inventors:

KIM H. MANWARING
MARK L. MANWARING

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MAYER, BROWN & PLATT
P.O. Box 2828
Chicago, Illinois 60690-2828

WATER CONTENT PROBE

FIELD OF INVENTION

2   The invention relates to an apparatus and method for measuring local brain water

content, perfusional pulsatile changes and the real time derivation of brain stiffness by

4   comparison of perfusional and intracranial pressure tracings.

BACKGROUND OF INVENTION

6   Monitoring intracranial pressure (ICP) in real time in intensive care units has

become an established standard of care in guiding physicians in the management of

8   severe head injury. Treatment of head trauma increases pressure on the brain requiring

monitoring intracranial pressure. This is particularly true in complicated cases of

10   hydrocephalus as a post-craniotomy adjunct to detect brain swelling and in selected

instances of brain infection and stroke. As brain swelling worsens due to the disease

12   process, baseline pressure and waveform changes signal the need to aggressively attempt

to reverse the course of the swelling with medications and pulmonary ventilation changes.

14   Intracranial pressure monitoring is normally performed by inserting a shunt

through a hole in the cranium. A ventriculostomy catheter connected to an external

16   pressure transducer is then introduced via the shunt into the brain substance. The shunt

may also be used to drain excess fluid from the brain substance. An external pressure

transducer provides accurate pressure measurements since a reliable baseline may be

2   established. However, an external pressure transducer requires invasive procedures,

risking a patient's health.

4   More recently, a miniaturized fiberoptic or strain gauge pressure transducer is

inserted into the brain substance. The miniaturized transducer greatly reduces the

6   invasiveness of the insertion procedure, but no practical method exists to establish a

baseline measurement. This creates accuracy problems since many factors over the

8   course of treatment may shift baseline measurements. Additionally, the ICP sensor and

data from it alone do not allow a direct measurement of how edematous or congested the

10   specific region of the brain is. Furthermore, swelling provides a widely ranging pressure

change related to age and causes of the swelling. Finally, the ICP sensor alone does not

12   provide a measurement of real time brain stiffness or compliance, a helpful indicator of

imminent deterioration risk.

14   Static measurement may be achieved by magnetic resonance imaging ("MRI"),

but this does not provide real time data. Real time information would greatly facilitate

16   the detection of true shunt failure in the management of hydrocephalus. However, since

real time measurement cannot be done with internal sensors, shunt failure must be

18   inferred from late presenting clinical deterioration and anatomical changes as seen in

imaging studies of the MRI. Additionally, the transport of a critically ill patient to an

20   MRI facility is hazardous.

There is therefore a need for an instrument which may be inserted through a single

2   aperture in the skull for simultaneous and continuous monitoring of both intracranial

pressure and cerebral water content. There is another need for an instrument which may

4   continuously measure pulsatile changes, altering apparent water content relating to beat-

to-beat tissue perfusion due to cardiac output of blood to the brain. There is a further

6   need for an instrument which provides the continuous measurement of tissue congestion

related to venous back pressure from mechanical ventilation. There is another need for an

8   instrument which derives the percent water content of the brain for comparison against

normal values. There is yet another need for a system to monitor the more gradual

10   baseline changes in wetness or brain edema of intracellular or extracellular origin related

to the disease process. There is another need for an instrument which can simultaneously

12   display the intracranial pressure (ICP) waveform and the pulsatile perfusional or

momentary congestion changes of the brain. There is still another need for an apparatus

14   and method for comparing the differences in lagtime between the ICP and perfusional

waveforms, from which a realtime measurement of brain stiffness or compliance is

16   derived.

SUMMARY OF THE INVENTION

18   These needs may be addressed by the present invention which is embodied in one

aspect of the invention which is a probe for measuring tissue water content in a region of

interest in the brain. The probe has an implantable tissue water content sensor having two

2   plates with a proximal and distal end. The two plates are separated by a dielectric

material and the distal end is implantable in brain tissue. An impedance matching circuit

4   is coupled to the proximal end of one of the plates. A first output terminal is coupled to

the matching circuit resistor and a second output terminal is coupled to one of the plates.

6   A remotely positioned frequency spectrum analyzer receives an output signal from the

first and second output terminals. A digital computer has a display, the digital computer

8   having an input coupled to the output signal from the water content probe and the

spectrum analyzer, the computer programmed to display the resonant frequency of the

10   sensor indicative of water content in the brain tissue.

Another aspect of the present invention is a method of measuring tissue water

12   content in a selected region of interest in the brain. A capacitive sensor having two plates

outside the selected region of interest is calibrated and the resonant frequency of the

14   sensor in air is determined. The capacitive sensor is calibrated in a mixture of water and

NaCl. The resonant frequency of the sensor in the mixture is determined. A linear

16   baseline frequency in relation to water content based on the resonant frequencies of the

sensor in air and the mixture is established. The capacitive probe is implanted through a

18   skull aperture such that the capacitive plates are exposed to the brain cortex and subjacent

white matter. Interrogatory frequency scanning by a spectrum analyzer coupled to the

20   sensor is produced to determine the center point of resonance by passage of the signal.

True tissue water content is approximated by curve-fitting the frequency of resonance

2   with the baseline frequency.

Another aspect of the present invention is a method of deriving beat-to-beat

4   perfusional and congestion changes in brain tissue. The method includes inserting a

water content probe having two conductive plates and a dielectric in the brain tissue.

6   Signals at different frequencies on the water content probe are sent. A standing wave

ratio at different frequencies is determined. A water content change tracing which

8   fluctuates with cardiac output pulsatile perfusion of the tissue is then determined.

Another aspect of the present invention is a method of deriving realtime

10   compliance or stiffness of brain tissue. The intracranial pressure of the brain tissue is

measured. An intracranial waveform from the measurements of the intracranial pressure

12   is then plotted. The pulsatile congestion changes in water content of the brain tissue is

measured. A pulsatile congestion change waveform is plotted from the measurements of

14   the pulsatile congestion change. The waveforms of intracranial pressure and the pulsatile

congestion change in water content on a computer are simultaneously plotted. The

16   stiffness of the brain is then determined from the simultaneous plotting.

Another aspect of the present invention is a probe for measuring tissue water

18   content in a region of interest in the brain. The probe has an implantable tissue water

content sensor having two plates with a proximal and distal end. The two plates are

20   separated by a dielectric material and the distal end is implantable in brain tissue. A

signal transmitting circuit is coupled to the proximal end of one of the plates. A signal

2   receiver is provided. A remotely positioned frequency spectrum analyzer is coupled to the

signal receiver. A digital computer is provided having a display and an input which is

4   coupled to the output signal from the water content probe and the spectrum analyzer.

The computer is programmed to display the resonant frequency of the sensor indicative of

6   water content in the brain tissue

It is to be understood that both the foregoing general description and the following

8   detailed description are not limiting but are intended to provide further explanation of the

invention claimed. The accompanying drawings, which are incorporated in and constitute

10   part of this specification, are included to illustrate and provide a further understanding of

the method and system of the invention. Together with the description, the drawings

12   serve to explain the principles of the invention.

BRIEF DESCRIPTION OF DRAWINGS

14   This invention is pointed out with particularity in the appended claims. However,

other objects and advantages together with the operation of the invention may be better

16   understood by reference to the following illustrations, wherein:

Fig. 1 is a perspective view of a brain stiffness probe according to an embodiment

18   of the present invention.

Fig. 2 is a partial cutaway view depicting the probe in Fig. 1 inserted through an

2   aperture in the skull such that it is exposed to direct contact with brain tissue.

Fig. 3 is a block diagram with the probe components and remotely placed

4   measuring equipment for both the water content sensor component and intracranial

pressure component according to one embodiment of the present invention.

6   Fig. 4A-Fig. 4D are frequency resonance curves and calibration and measurement

of tissue water content taken using a system according to the present invention.

8   Fig. 5 is a waveform diagram showing pulsatile changes in microscopic center

frequency shifts in the water content probe according to the present invention due to

10   perfusion of the brain by cardiac pulsatile output.

Fig. 6 is a block diagram of a wireless implementation of a water content probe

12   according to the present invention.

Fig. 7A-7B are waveform diagrams which show the phase or lagtime relationship

14   between the pressure waveform and perfusional waveform derived from the water content

component of the combined probe according to the present invention.

16   **DESCRIPTION OF THE PREFERRED EMBODIMENT**

While the present invention is capable of embodiment in various forms, there is

18   shown in the drawings and will hereinafter be described a presently preferred

embodiment with the understanding that the present disclosure is to be considered as an

exemplification of the invention, and is not intended to limit the invention to the specific

2 embodiment illustrated.

In accord with one embodiment of the invention, a combined probe 10 for

4 measuring brain wetness and intracranial pressure is shown in FIG. 1. The probe 10 has a

water content sensor 11 which has two conductive plates 12 and 14 on opposite sides of a

6 printed circuit board (PCB) substrate 16. The conductive plates 12 and 14 are silver in

the preferred embodiment but any suitable conductor material may be used. The substrate

8 16 in the preferred embodiment measures 5 cm in length, 2 mm in width, and 0.5 mm in

depth. The probe 10 has a proximal end 18 and a distal end 20. Multiple holes 22 extend

10 across the PCB substrate 16. The holes 22 increase sensitivity to real time pulsatile

perfusional changes in tissue as they increase the surface area in contact with the brain

12 tissue. The proximal end 18 has a surface mount resistor 24 on one side. A coaxial cable

26 has a core conductor member 28 and a shielding conductor 30 which is

14 circumferentially located around the core member 28.

The surface mount resistor 24 is coupled between the proximal end 18 and one

16 end of the coaxial cable 26. The surface mount resistor 24 provides impedance matching

between the core 28 of the coaxial cable 26 and the plate 12. The impedance matching

18 provided by the surface mount resistor 24 and the cable 26 is employed to achieve noise

immunity in the cable 26 and allow the analysis electronics to be located at a distance

20 from the water content sensor 11. Other types of impedance matching circuits such as a

balanced antenna approach may be used as well. The plate 14 is connected directly to the

2   shielding conductor 30 of the coaxial cable 26. The other end of the coaxial cable 26 is

connected via an adapter 32 to a controller unit 34. In this sample, the adapter 32 is a

4   PL250 type which minimizes signal loss to the cable 26.

The water content sensor 11 is inserted through a plastic bolt 36 via an aperture

6   38. The plastic bolt 36 has a pair of hex nuts 40 and 42 which are mounted on a main

body section 44. The main body 44 has an exterior surface with threads. A lug nut 46 is

8   coupled to the main body 44 and has corresponding interior threads. The lug nut 46 may

be rotated on the main body 44 and provides a connection for the cable 26.

10   The probe 10 is inserted to a depth in brain tissue up to the plastic bolt 36 via the

aperture. The hex nuts 40 and 42 and the lug nut 46 are tightened on the main body 44 of

12   the bolt 36 to provide a seal and to allow the plastic bolt 36 to be positioned and held in

the aperture 38.. The bolt 36 is designed such that the surface mount resistor 24 lies

14   about 1 mm above the surface of the brain, placing nearly the full length of the plates 12

and 14 in the brain tissue. Since the water of the brain bears a moderate salinity (typically

16   130 -150 mEq Na+ per 1000 ml), an extremely thin-sputtered layer of insulation 50

insulates the electrical plates 12 and 14 from direct tissue contact. The insulation layer 50

18   is Teflon in the preferred embodiment, but any type of insulation may be used. The

insulation layer 50 allows the point of resonance of the water content sensor 11 to be

20   precisely measurable. The configuration of the capacitive plates 12 and 14 may be used

in a tubular configuration to allow a silicone external ventricular drain through the lumen.

2   In such a configuration, the electrically conductive plate surfaces are located on the length

of the tube on opposite hemispheres to create a similar capacitive effect.

4   FIG. 2 shows a cutaway view of a head 60 with a brain 62 shown through the

frontal lobes as seen by a typical MRI. The brain 62 is encased by a cranium 64. The

6   containment of the cranium 64 creates pressure on the brain 62 which may be excessive

due to fluid buildup. A skull aperture 66 (or burr hole) is created in the cranium 64 after

8   a scalp incision. This routine procedure in the intensive care unit would normally be

followed by the introduction of an ICP sensor or ventriculostomy catheter as is presently

10 known.

The plastic ventriculostomy bolt 36 in the preferred embodiment is commercially

12 available through Codman and Shurtleff Incorporated, Raynham, Massachusetts. The

plastic bolt 36 is tapped and threaded snugly into the cranium 64. The water content

14 sensor 11 is passed through the bolt 36 to a depth such that the sensing capacitive plates

12 and 14 are exposed to cortex and white matter of the brain 62. The plastic bolt 36

16 provides stable fixation of electrical connections and prevents movement of the sensor 11

in the brain 62 by secure fixation at the skull aperture 66 (burr hole).

18 An intra cranial pressure ("ICP") sensor 70 passes through the bolt 36 into the

subjacent cortical tissue of the brain 62. The ICP sensor 70 is an electrical strain gauge

20 type and measures changes in resistance due to pressure. Alternatively, any implantable

pressure sensor such as a fiber optic sensor may be used. A fiber optic sensor has lasers

2   coupled to dual fiber optic cables. A diaphragm is coupled to the end of the fiber optic

cables and distorts light in reaction to pressure, producing changes in either light

4   amplitude or frequency. In other cases, an external strain gauge which is coupled via

tubing to a ventriculostomy catheter or a cranial bolt may be used to measure pressure.

6   The output voltage of the ICP sensor 70 is carried by a cable 72. The strain gauge

ICP sensor 70 in this example is commercially available from Codman and Shurtleff

8   Incorporated, Raynham, Massachusetts but any appropriate pressure sensor may be used.

The ICP sensor 70 may be inserted separately from the bolt 36 and/or inserted at a

10   separate site on the cranium if desired. This is to be avoided in most cases, but certain

circumstances may require the separate insertion of the ICP sensor 70 and the water

12   content sensor 11.

The respective wiring connections to and from the water content sensor 11 and the

14   ICP sensor 70 are coupled to the controller unit 34 which is at a remote location.

Alternatively, the cables may be connected to a signal transmitter if it is desired to

16   eliminate the cables. The technique of positioning the combined sensors is identical to

the routine insertion of a ventriculostomy catheter for monitoring and carries with it the

18   same acceptably low risks.

Figure 3 is a block diagram of the control unit 34 of the combined ICP-water

20   content probe 10. The ICP sensor 70 is a strain-gauge type which has a wheatstone

bridge 74 of standard configuration having a pressure transducer 76 and three resistors 78,

2   80 and 82. The voltage of the bridge 74 changes in accordance to pressure changes on the

pressure transducer 76. The output voltage of the bridge 74 represents the sensed

4   pressure on transducer 76 and is coupled to the input of an analog to digital convertor 84

via the cable 72. The output of the analog to digital convertor 84 is coupled to a digital

6   computer 86.

The water content sensor 11 is coupled via the coaxial cable 26 to an input of a

8   spectrum analyzer 88. The spectrum analyzer 88 in the preferred embodiment is an AEA-

Tempo 150-525 Analyst manufactured by Tempo Research of Vista, California. The

10   spectrum analyzer 88 sweeps an interrogating frequency from 150 MHZ to 550 MHZ

every 2 seconds to the water content sensor 11 in the preferred embodiment. The

12   frequency spectrum for measuring brain water content without interference from other

sources is optimally measured between 400 and 600 MHZ. However, other ranges may

14   be useful depending on the probe length.

The direct output from the spectrum analyzer 88 is coupled to the digital computer

16   86 and a second output is coupled to an analog to digital convertor 90. This allows

display of the resonant frequency of the water content sensor 11 determined from the

18   direct output, as well as heart beat to heart beat changes in frequency and standing wave

ratio (SWR) from the digital to analog converter 90. The outputs from the spectrum

analyzer 88 and the digital to analog convertor 90 are plotted on a display 92. The

2   display 92 is preferably a high resolution monitor but any display device may be used.

The digital computer 86 contains software necessary to simultaneously display the

4   pulsatile waveform outputs from the ICP sensor 70 and the water content probe 11 on the

display 92. As will be explained below, the brain water content and blood congestion

6   alter the resonant frequency of the water content probe 11 and provides an indication of

the real time read out of apparent tissue water content and the stiffness of the brain 62

8   which is independent of baseline water content or pressure.

FIGs. 4A-4D illustrates the process of probe calibration and water content

10   determination of brain tissue which is displayed using the software on the digital

computer 86 in conjunction with the display 92. The water content sensed by the water

12   content sensor 11 of the probe 10 in FIGs. 1 and 2 is indicative of the effect of the

surrounding tissue dielectric on the speed of transmission of the interrogating signal

14   through the plates 12 and 14. Similar in concept to time domain reflectometry and

familiar to those skilled in the art, the spectrum analyzer 88 will display a resonant

16   frequency when the water content sensor 11 is placed in tissue. This resonance is a

function of plate capacitance of the plates 12 and 14 (most strongly affected by probe

18   length in this configuration) and the adjacent dielectric of the material of the substrate 16.

The PCB dielectric material 16 between the plates 12 and 14 and the extremely thin-

20   sputtered layer 50 have dielectric constants near air (dielectric of 1). In contrast, the brain

is normally about 70% water. As the dielectric of H2O is 80, the tissue water content

2   overwhelmingly determines the resonant frequency measured from the water content

sensor 11.

4   FIG. 4A shows the output plot of the spectrum analyzer 88 displayed by the digital

computer 86 when the water content sensor 11 is entirely exposed to air. Since no

6   significant water content related dielectric slows the signal in air, the resonant frequency

of the water content sensor 11 is 440 MHZ. FIG. 4B shows the output plot when the

8   water content sensor 11 is inserted in a 100% normal saline and water compound

(simulating brain water and salinity). The resonant frequency of the water content sensor

10   11 has decreased to 167 MHZ as shown in FIG. 4B. This reduction is due to the

overwhelming dielectric effect of the surrounding water with its high dielectric constant.

12   FIG. 4C shows the sharp resonant curve of the output of the water content sensor

11 when placed in the brain tissue 62 as shown in FIG. 2. The resonant frequency is 307

14   MHZ in FIG. 4C. The water content of the brain tissue 62 is proportional to the resonant

frequency. The different resonant frequencies sensed by the sensor 11 in differing

16   conditions of water content may be plotted. FIG. 4D shows the linearity of a typical

output curve from the water content sensor 11 from submersing the sensor 11 in water as

18   in FIG. 4A to full exposure in air as in FIG. 4B. By testing the water content sensor 11 in

tissue utilizing dry and wet weight water content determinations, the linear range of

clinical significance from 65% (very dehydrated brain) to 80% (very edematous brain)

2   may be tested and provides a measurement standard for water content determination.

The measurable accuracy of the water content sensor 11 is up to 0.1% of water

4   content change. In clinical use, however, the absolute local water content determination

is not as useful as the trending of water content of the brain tissue over the course in the

6   intensive care unit against a baseline measurement. The long term trends are more useful

data since insertion of the water content sensor 11, as any probe, into the brain 62, causes

8   a temporary injury edema which develops about the sensor 11 and artificially increases

the baseline water content in the region. Additionally, effects of local minor

10   accumulation of a non-flowing blood clot against the sensor plates 12 and 14 or

incomplete passage to full depth of the plates 12 and 14 will offset the true water content

12   baseline. Despite these considerations, the baseline measurement is used as a control

against the course of illness and therapeutic intervention with dehydrating drugs such as

14   furosemide and mannitol or ventilator changes provide a real time feedback of impact of

the physician's regimen on the patient.

16   When the baseline water content is plotted over hours of time on a computer such

as the computer 86, gradual shifts in the water content may be analyzed. For example,

18   the initial shift in water content represents the initial placement edema and its resolution.

The longer term shift in water content may represent the trend of brain swelling in the

20   region of monitoring, edema due to head injury, or the effects of therapy. Alternatively,

the changes in resonant frequency may also be logged using a spectrum/frequency

2   analyzer such as a Model HP8568A manufactured by Hewlett-Packard. However, much

smaller changes of significance to the course of the illness may be measured from heart

4   beat to heart beat as will be explained below. Thus, the water content sensor 11 may be

used in isolation without the associated intracranial pressure sensor 70, yielding profitable

6   data for the patient.

FIG. 5 shows a pulsatile baseline 500 obtained from minute apparent water

8   content change. Either one of two techniques may be used to obtain the water content

change on a heart beat to heart beat basis. The first technique involves use of the

10   frequencies around the resonant frequency. When the spectrum analyzer 88 is employed

to identify the standing wave ratio ("SWR") at resonance, a properly placed water content

12   sensor 11 will show an SWR of 1.0. The frequency of resonance relates to the water

content which is 307 MHZ in FIG. 4D.

14   However, if the frequency just to the right of the resonant point in FIG. 4D is

selected where maximum change in SWR occurs per unit frequency change, typically an

16   SWR of about 1.15, the beat-to-beat change of SWR may be plotted. The beat to beat

SWR changes thus correlates to the local increased water content sensed by the water

18   content sensor 11 which is due to transient increased tissue congestion and arteriolar

dilation due to blood flow. An undulating waveform 502 as a function of time is shown

20   in FIG. 5. The undulating waveform 502 is measured from the water content sensor 11 as

a function of the change in SWR from heart beat to heart beat. A slower baseline

2   undulation relates to back pressure on the venous side of the brain from positive pressure

ventilation of the patient or may be evoked by transient jugular vein compression (termed

4   the Queckenstedt maneuver).

Alternatively, the beat-to-beat effect may be measured by tracking the center

6   frequency of resonance deviation when the water content sensor 11 in FIGs. 1 and 2 is

viewed as the variable component of a simple LC resonant circuit 100 as shown in FIG.

8   6. The sensor 11 is coupled to an inductor 102. The sensor 11 and the inductor 102 may

thus be integrated in an implanted sensor unit 104. A second inductor 106 is coupled to

10   the processing circuitry which includes a signal generator and resonant frequency

measurement device as explained above. Since the value of the first inductor 102 is

12   fixed, the resonant frequency will shift as a function of water content of the tissue

surrounding the sensor unit 104. The resonant frequency is measured wirelessly by

14   sensing magnetic field energy from the second inductor 106 and the signal generator.

A significant advantage of this approach is that beat-to-beat pulsatile changes and

16   baseline water content may be measured wirelessly using a spectrum analyzer pick-up

circuit across the scalp from a wholly implanted resonant circuit. This technique allows

18   long term, wireless monitoring of a region of interest over months to years for

determining optimal compliance and control of hydrocephalus in patients treated by a

20   ventriculoperitoneal shunting procedure.

With reference to FIGs. 1 and 2, when the intracranial pressure (ICP) waveform is

2   plotted simultaneously with the pulsatile water content waveform derived from the two

techniques described above, a phase relationship between the waveforms is seen. FIG.

4   7A shows a simultaneous plot of pressure 600 versus a pulsatile water content plot 602.

The pressure plot 600 precedes pulsatile congestion as sensed by the water content probe

6   plot 602. This indicates that peak vascular congestion lags peak pressure. FIG. 7A

depicts the phase relationship plotted of a healthy, normal brain. In FIG. 7A, brain

8   stiffness is within acceptable levels and thus the phase of beat to beat water content

resonant frequency is phase shifted from the pressure changes by 115 degrees.

10   In contrast, FIG. 7B shows the pressure and water content plots 600 and 602

superimposed on each other in an example of worsening brain compliance or stiffness.

12   The beat to beat water content resonant frequency is phase shifted from the pressure

changes by 68 degrees. This relationship is also demonstrated by a combined ICP-blood

14   flow probe such as when monitoring a patient with a thermal probe as described in U.S.

Patent No. 4,739,771 to the same inventors and incorporated by reference herein. In a

16   normal, relaxed brain, the peak flow or vascular congestion may lag substantially,

especially in a child with an open antereor fontanel. As the brain becomes progressively

18   swollen with brain edema in head injury the lag narrows until the two waveforms are

essentially co-incidental. Similarly, poor compliance in a patient with shunt failure will

20   show the pattern of narrowing of lag time. The relationship can also be measured in real

time as a function of phase lag adjusted for frequency (heart beat), akin to phase lag

2   plotting in current phase compared to voltage phase in inductive circuits. Thus, the

relationship by lag in seconds or phase angle adjusted for frequency provides a measure

4   of brain stiffness which is independent of transducer amplitude, accuracy or stability,

allowing a frequency domain relationship applicable to long term monitoring including

6   implants.

It will be apparent to those skilled in the art that the disclosed measurement

8   method and apparatus described above may be modified in numerous ways and assume

many embodiments other than the preferred forms specifically set out and described

10   above. Alternatives to the capacitive water content sensing technology include time

domain reflectometry and square-wave frequency based sensors as well as fiberoptic

12   sensors. The time domain reflectometry views the sensing components as a model

transmission line. The reflection of a signal is measured as a function of water content.

14   The square wave frequency based sensor uses a broad range of frequencies to determine

water content as a function of the frequencies observed. The proper interpretation of the

16   square wave frequency signals requires the appropriate circuitry. The fiberoptic sensor

uses a light signal of a certain wavelength which is propagated down an implanted fiber.

18   An optical grating is used to determine reflection of the light signal which is a function of

the water content.

The pulsatile flow relationship to the ICP waveform can be derived by use of

2   transducers such as thermistors (as described in the author's cited patent), or other heat

clearance transducers as well as by transcranial impedance measurement and local tissue

4   laser Doppler technique. The transcranial impedance measurement is performed by

placing an ohmmeter on the head and measuring the signals at high frequency. An

6   alternate impedance measurement may be used using a four probe method. Two

impedance probes measure the output while two probes input the signal. The laser

8   Doppler technique uses a laser to send a signal to the tissue of interest. The shift in

Doppler frequency is measured to determine the water content.

10   An antenna sensor may be used for the water content sensor instead of the

capacitive approach explained above. The entirety of the circuitry which includes the

12   implanted circuit with an antenna to sense the water content in the tissue and a transmitter

can be reduced to an integrated circuit as part of an implant or integrated onto the probe

14   itself, allowing transcranial, wireless interrogation. The present invention is not limited

by the foregoing descriptions but is intended to cover all modifications and variations that

16   come within the scope of the spirit of the invention and the claims that follow.